Comment on "Correlation of the Highest-Energy Cosmic Rays with Nearby Extragalactic Objects"

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We argue that the data published by the Pierre Auger Collaboration (arXiv:0711.2256) disfavor at 99% confidence level their hypothesis that most of the highest-energy cosmic rays are protons from nearby astrophysical sources, either Active Galactic Nuclei or other objects with a similar spatial distribution.

The Pierre Auger Collaboration reported a remarkable correlation (*1*) between the arrival directions of ultra-high energy cosmic rays (UHECR) and positions of nearby Active Galactic Nuclei (AGN). The correlation was found by scanning over the maximum angular separation, the minimum event energy and the maximum AGN redshift, see Ref. (*2*) for the details of the method. The best signal was found at the angle of 3.1° for the cosmic-ray set consisting of 15 events with reconstructed energies $E > 5.6 \times 10^{19}$ eV and for the set of 472 AGN obtained by imposing the cut on the redshift, $z \leq 0.018$, in the catalog (*3*). The correlation was tested with the independent set consisting of 13 events, with the parameters fixed *a priori* from the first

data set. The probability that the correlation has occurred by chance is 1.7×10^{-3} as derived from the independent set. The conclusion was made that the anisotropy of arrival directions is consistent with the hypothesis that "most of the cosmic rays reaching Earth in that energy range are protons from nearby astrophysical sources, either AGN or other objects with a similar spatial distribution." We refer to this proposition as the "AGN hypothesis" in what follows. Crucial ingredients of this hypothesis are nearly rectilinear propagation of UHECR and a large (*4*) number of sources distributed similarly to AGN which in turn follow the matter distribution (*5*).

In this Comment we would like to point out that, given the data presented in Ref. (*1*), the AGN hypothesis is unlikely. We should stress that we question neither the fact nor the derived significance of the correlation. It is the interpretation of Ref. (*1*) that we put in doubt.

The flux of a given source decreases as $1/r^2$ with the distance r to the observer. This is not taken into account in the method of positional correlations used in Ref. (*1*). Here we present statistical tests which include this suppression factor.

The distribution of matter (and, therefore, of AGN) in the nearby Universe is very inhomogeneous. The role of local inhomogeneities is enhanced by the cosmic-ray attenuation that cuts off the (uniform) flux coming from distant sources. The AGN hypothesis implies that when the suppression factors are properly taken into account, major local structures such as the Centaurus and Virgo superclusters provide sizeable contributions to the cosmic-ray flux at highest energies.

This prediction of the AGN hypothesis allows for statistical tests different from the small-scale correlation analysis. Fig. 1 shows the UHECR events used in the analysis of Ref. (*1*) together with the expected flux of cosmic rays simulated assuming the AGN hypothesis. One may identify the Virgo and Centaurus superclusters. The expected numbers of events from AGN in these two structures are nearly equal. It is seen in Fig. 1 that there is a deficit of observed events from Virgo as well as from other local structures, except the Centaurus supercluster. This

suggests that the AGN hypothesis proposed in Ref. (*1*) may be disfavored.

To quantify this statement we took the sample of AGN used in the analysis of Ref. (*1*). According to the catalog classification (*3*), this sample consists of 457 AGNs, 14 quasars and 1 probable BL Lac object, Cen A. We removed from the sample 3 objects with $z = 0$ classified as stars in the database (*6*). We calculated the expected number of events within given angular distance from the center of the Virgo cluster assuming $1/r^2$ suppression of the flux, and compared it to the data. The results are presented in Fig. 2. The observed and expected distributions of events are inconsistent. According to the Kuiper test, the probability that the observed and simulated events are drawn from the same distribution is 2×10^{-4}. The main origin of inconsistency is clear: of 27 events, ~ 6 are expected to come from Virgo under the AGN hypothesis while none is observed. The probability of this is 10^{-3}, in agreement with the Kuiper test.

Similar results are obtained in tests which do not use the Virgo supercluster as a reference point. Comparing the Galactic longitudes of observed and expected cosmic rays we find that the probability that the two samples are drawn from the same distribution is 2% according to the Kuiper test, while for the Galactic latitude the corresponding probability is 10^{-4}. Analogous tests for the Supergalactic longitude and latitude give the probabilities of 7% and 10^{-4}, respectively. We conclude that the AGN hypothesis of Ref. (*1*) is disfavored at the confidence level of at least 99%.

If, as it is suggested by the above arguments, the highest-energy cosmic rays observed by the Pierre Auger Observatory do not come from sources that follow the local matter distribution, how can one explain the observed correlations with AGN? One possible explanation could be the existence of a nearby bright source which happened to be in the direction to the Centaurus supercluster where the density of background AGN is larger than in average. Cen A is a natural candidate. Contrary to the AGN hypothesis, this explanation would imply one or at most a few sources in the nearby Universe and large deflections, due to either strong magnetic fields or to

the presence of heavy nuclei in the cosmic-ray flux as suggested in Refs. (*7,8*). In that case the properties of the highest-energy cosmic rays may appear different if seen from the Southern and Northern hemispheres.

To summarize, the data presented in Ref. (*1*) disfavor the hypothesis that most of the highest-energy cosmic rays come from nearby astrophysical sources, either AGN or other objects with a similar spatial distribution. The alternative explanation of the observed correlations could be, e.g., the existence of a bright source in the direction of the Centaurus supercluster, Cen A being a possible candidate.

References and Notes

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4. According to the statistics of cosmic-ray clustering at small angles (*10*), the number of sources contributing to the flux is expected to be at least of order several hundred assuming the AGN hypothesis.

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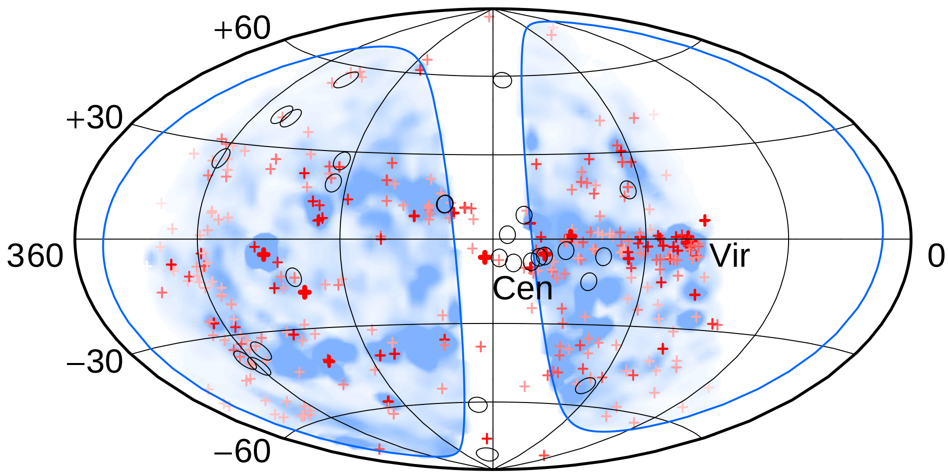

Figure 1: Hammer projection of the celestial sphere in supergalactic coordinates with crosses at the positions of nearby AGN from the sample used in the correlation analysis of Ref. (*1*). The color saturation of a given cross indicates the expected cosmic-ray flux with the account of the acceptance of the Pierre Auger Observatory (PAO) and the $1/r^2$ suppression, r being the distance to the source. Open circles represent 27 highest-energy cosmic rays detected by PAO. Shading shows the expected cosmic-ray flux from sources that follow the local matter distribution (for details see Ref. (*9*)), smoothed at the angular scale of 3.1° and convoluted with the PAO acceptance (darker regions correspond to larger cosmic ray flux). Blue lines cut out the region with Galactic latitude $|b| < 15^\circ$ where the latter flux cannot be determined because of incompleteness of the source catalog. The positions of the Centaurus (Cen) and Virgo (Vir) superclusters are indicated.

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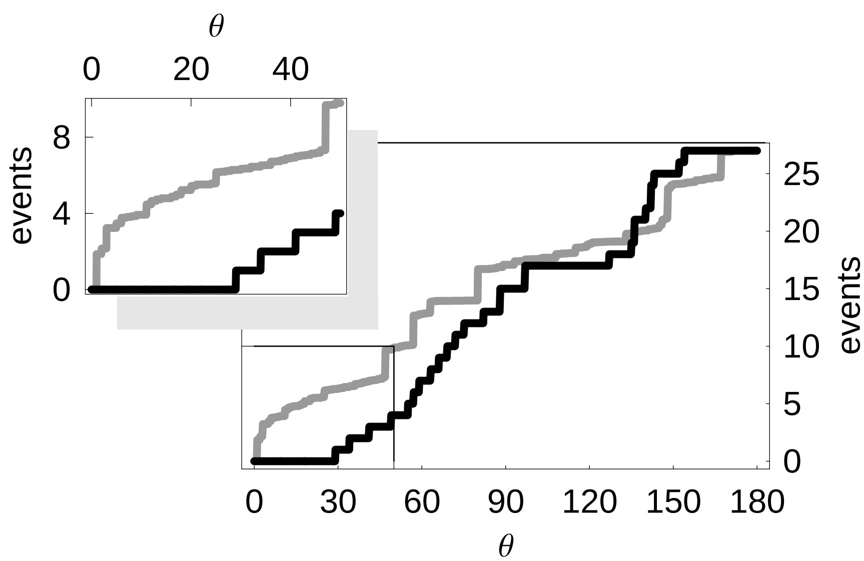

Figure 2: Number of events in the circle of radius θ (in degrees) centered on the Virgo cluster as determined in (*6*): gray, expected number of events assuming the AGN hypothesis; black, events actually observed, Ref. (*1*). The side panel zooms on the region around Virgo.